Renewable and Sustainable Energy Reviews 30 (2014) 701–714

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy and hydraulic efficiency in conventional water supply systems

Mateus Ricardo Nogueira Vilanova [a,*], José Antônio Perrella Balestieri [b]

[a] Universidade Estadual Paulista, UNESP, Faculdade de Engenharia de Guaratinguetá, Programa de Pós-graduação em Engenharia Mecânica, Transmissão e Conversão de Energia, Av. Dr. Ariberto Pereira da Cunha, 333, Guaratinguetá, SP, Brazil

[b] Universidade Estadual Paulista, UNESP, Faculdade de Engenharia de Guaratinguetá, Departamento de Energia, Av. Dr. Ariberto Pereira da Cunha, 333, Guaratinguetá, SP, Brazil

ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form
27 October 2013
Accepted 13 November 2013
Available online 30 November 2013

Keywords:
Water supply utilities
Electricity conservation
Rational use of water

ABSTRACT

This paper presents the state-of-the-art approaches to energy (electricity) and hydraulic efficiency and conservation in conventional water supply systems, providing an overview of energy efficiency and conservation alternatives from the analysis of selected research literature. These alternatives vary from leakage management to state-of-the art real-time optimization techniques, and can be classified into three dimensions according to their natures: project and design dimension, operational dimension and physical dimension. The potential energy savings and the impact of these alternatives over the water supply systems' energy efficiency are highly variable. All the energy efficiency and conservation alternatives analyzed in this work may contribute with the promotion of sustainability of conventional water supply systems.

Contents

1. Introduction

Water and energy resources are fundamental to human existence, and are regularly subject to economic, technological, demographic and social pressures. It is estimated that 2–3% of the worldwide electricity consumption is used for pumping in water supply systems (WSSs) [1], while 80–90% of this consumption is absorbed by motor-pump sets [2,3]. This cost represents one of the major operational costs associated with WSSs.

Water pumping in WSSs and the other inter-relationships between water and energy (i.e., hydroelectric and thermoelectric generation, fuel and biofuel production, water supply, pumping and water treatment, desalination) will intensify if predictions regarding global climate change are confirmed. In this sense, while the production and use of energy from fossil fuels is considered the main cause of global warming, the most drastic consequences

* Correspondence to: Rua Rodrigues Seabra, 404, Bairro Morro Chic, Itajubá-MG, CEP 37.500-079, Brazil. Tel.: +55 35 36220959, Mobile: +55 35 91348406.
E-mail addresses: mathidr@yahoo.com.br,
mateusrnv@gmail.com (M.R. Nogueira Vilanova),
perrella@feg.unesp.br (J.A. Perrella Balestieri).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.11.024

of climate change, such as floods, storms, droughts, and water-borne diseases, have been attributed to water.

Shrestha et al. [4] states that considering the critical links between water and energy during water planning and policy making can lead to significant energy savings. In turn, these savings have the potential to reduce the associated CO_2 emissions. The availability of drinking water in the near future will also require adaptations in several regions of the world in response to changes in precipitation and runoff patterns, salinization and alterations in water source quality as a result of climate variability [5]. However, most of the adaptive technological alternatives to these issues are energy-intensive (e.g., desalination and water reuse) [6].

According to Gude et al. [7], the electricity consumed (described by the energy intensity) by the desalination process varies from 1.5 kWh m^{-3} in multi-effect distillation and multi-effect distillation with thermal vapor compression processes to 12.0 kWh m^{-3} when mechanical vapor compression processes are engaged. Based on a literature review, Plappally and Lienhard [8] reported electrical intensities in the range of 0.27 kWh m^{-3} to 3.8 kWh m^{-3} for urban wastewater reuse and recycling plants. The same authors reported the medium specific energy intensity (energy intensity divided by the elevation head) of groundwater pumping in California to be 0.004 kWh m^{-3} m^{-1}. Table 1 presents the energy intensities associated with conventional water supply systems (CWSSs) as reported in literature, which vary from 0.25 kWh m^{-3} to 4.5 kWh m^{-3} depending on the source type (i.e., surface or groundwater).

Promotion of the efficient and rational use of water and electricity in WSSs plays a strategic role in the quest for the sustainable development of nations as well as in the mitigation of and adaptation to the causes/consequences of climate change. The high potential for the application of water and electricity rational use actions in WSSs has been attributed to poor infrastructure and operational procedures, particularly in developing countries. Moreover, according to the Millennium Development Goals (MDGs) [14], there is a need for more sustainable alternatives in the expansion and implementation of new systems by the year 2015; further, according to the MDGs, there is a target to halve the proportion of people without sustainable access to safe water and basic sanitation.

Given the relevance of this theme, the present work presents a review of the alternatives and opportunities to promote water and electricity efficiency and conservation in CWSSs. CWSSs are systems in which the treatment is carried out by conventional coagulation, flocculation, settling and filtration; additionally, in CWSSs, the majority of electricity consumed is generally attributed to the power demand associated with pumping (for water catchment, adduction and distribution). The use of this delimitation in our study was defined based on the widespread use of such systems around the world in addition to the great potential for efficiency improvement, which typically can be identified in pumping systems, a fact which assigns an applied nature to this research.

This paper is focused on the supply side of management and alternatives and does not consider the opportunities and technologies available for energy and water conservation on the demand side of water management. Only the direct electricity consumption in CWSSs is considered, disregarding the energy consumption implicit in the various inputs (e.g., chemicals, materials) used in these systems; the energy consumed by the inputs is usually evaluated through life cycle analysis. We also disregard other energy flows beyond hydraulic and electrical; for example, the thermal energy embodied in the water masses flowing through the system is not considered here.

This paper is organized as follows: Section 2 presents the energetic and hydraulic model considered in this work, which summarizes the energy and mass flows in CWSSs. Section 3 presents a general approach to energy efficiency (EE) and energy conservation (EC) interventions and actions. As proposed by Dias [15], this general approach involves the classification of EE and EC actions in intervention classes, which allows both the impact of each measure on the EE of the system as well as the complexity of the measure's implementation to be inferred. Subsequently, these actions and interventions are contextualized to CWSSs, for which we identified three dimensions to evaluate the use and possibilities of energy conservation, including (1) the project and design dimension, (2) the operational dimension and (3) the physical dimension. The subsections of Section 3 detail the main opportunities for energy conservation applied to the CWSSs identified in the literature. In Section 4, we evaluate the opportunities described in Section 3; additionally, we evaluate some theoretical and empirical results of the applications of these opportunities. This evaluation includes the classification of EE and EC actions and opportunities in accordance with their impact on the energy efficiency of the system; this evaluation also explores their associated level of intervention, as described in Section 2.

2. The energy and hydraulic model of CWSSs

A water supply system is a set of structures, facilities and services that produces and distributes water to consumers;

Table 1
The energy intensities and indicators associated with CWSSs.

Authors	Region	Indicator description	Indicator values
Racoviceanu et al. [9]	Canada, Toronto	Energy intensity in the operation phase of water supply and treatment	0.68 kWh m^{-3}
Mo et al. [10]	USA, Florida	Energy intensity in the operation and maintenance phases of surface water supply due to direct energy use	1.33 kWh m^{-3}
	USA, Michigan	Energy intensity in the operation and maintenance phases of groundwater supply due to direct energy use	1.69 kWh m^{-3}
Scott et al. [11]	USA, Arizona	Energy intensity of water pumping in the Central Arizona Project	1.24 to 2.55 kWh m^{-3}
Venkatesh and Brattebø [12]	Norway, Oslo	Energy intensity in the operation and maintenance phases of water supply	0.39 to 0.44 kWh m^{-3}
Brasil [13] (indicators calculated by the authors with data from Brazilian National Sanitation Information System)	Brazil	Medium energy intensity of the Brazilian largest regional water companies	0.69 kWh m^{-3}
Plappally and Lienhard [8] (the authors presented values of indicators based on a literature review)	Canada, Ontario	Energy intensity of water extraction from wells	0.25 to 3.02 kWh m^{-3}
	USA, Northern Caroline Australia, Sydney	Energy intensity of surface water pumping	2.4 kWh m^{-3}
	USA, California	Energy intensity of water conveyance	1.6 to 2.6 kWh m^{-3}
	Mexico, Tijuana	Energy intensity of water conveyance	4.5 kWh m^{-3}

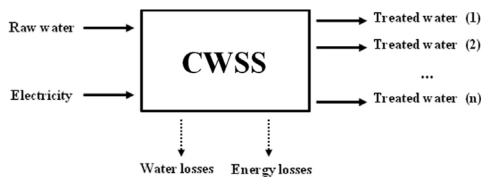

Fig. 1. The energy and hydraulic flows in CWSSs.

the distributed water must be compatible with the needs associated with the domestic consumption, utilities, and other industrial consumption in both quantity and quality [16]. Physically, the system is composed of a set of reservoirs (natural sources of raw water, storage and distribution tanks), pipes (water mains, distribution network pipes), civil structures (mainly in water treatment plants), and hydro-mechanical (pumps, valves) and electrical (motors) equipment.

To develop an energy and hydraulic model, a CWSS must be evaluated in terms of the mass (raw and treated water) and energy (electricity and hydraulic heads) flows, which vary in space and time. Fig. 1 illustrates the mass and energy flows based on the delimitations of this research; these delimitations do not consider the implicit thermal loads in the masses of water or chemicals used in the treatment process. Raw water, evaluated according to mass flow and hydraulic head, and electricity are the input of CWSS for producing treated water (that are also evaluated with mass flow and hydraulic head) for "*n*" consumers; water and electricity losses must also be considered in the model.

The input mass flow to the system corresponds to the raw water obtained from natural sources (surface or underground). The imported water flows are disregarded for the purpose of this research. The water flow carries a gross energy content that corresponds to the hydraulic head (a sum of the potential, piezometric and kinetic heads), which may be natural (due to gravity or from a pressurized underground water source) or artificial (the hydraulic head provided by pumping). When artificial hydraulic heads are present, electricity consumption is generally associated with the coupling of electric motors to pumps. After entering the system, the raw water passes through the conventional treatment process, followed by reservation (storage) and distribution.

The movement of water within the system requires aggregation of the hydraulic head to its mass, either by gravity or through the use of electrical energy for pumping. Part of the energy (electrical and hydraulic) and mass (raw and treated water) is lost due to the low efficiency of the equipment, bad operational practices (the maintenance of excessive water levels and pressures, for example), inadequate design and the presence of disabled structures (leakages in pipes, cracks in reservoirs, among others).

The useful output produced by a CWSS is the mass of treated water that the consumers actually receive at the appropriate pressure levels (which in the last instance corresponds to the energy content). Thus, the energy and hydraulic efficiency and the energy conservation in a CWSS can be evaluated as an optimization problem, in which the volume of raw water extracted from the source and the electrical energy consumed by the system are minimized simultaneously. The minimization process is subject to the appropriate service levels with respect to the providing of treated water in adequate volumes and pressures, according to the consumers' demands and locations.

3. The technological alternatives for energy and hydraulic improvements in CWSSs

According to Dias [15], the rational use of energy aims to provide sustainable development through the correct use of energy resources at all stages of conversion. Based on the author's description, the efficient use of energy can be systematized into the following six intervention levels.

- Level 1, the elimination of waste: waste elimination is the most evident level of intervention. In the context of water supply, the most emblematic example of intervention level 1 is the elimination of water losses due to leakages.
- Level 2, increasing the efficiency of power-consuming units: this level includes energy efficiency measures aimed at the technological improvement of processes, which involve, for example, the replacement of old motor-pump sets by high efficiency sets.
- Level 3, increasing the efficiency of power generation units: this levels aims to adjust and harmonize the energy production units with the energy consumption units, preferably *a posteriori* with respect to the level 1 and level 2 interventions. In the context of the present work, we can cite the following examples of level 3 interventions in WSSs, such as the use of renewable sources for water pumping and hydropower recovery.
- Level 4, the reuse of natural resources by recycling and reduction of the energy content of products and services: Dias [15] describes level 4 interventions as those related to the recycling and recovery of energy from waste generated in the considered production process as well as the use of technologies and inputs with reduced energy intensities throughout their lifecycles. Although outside the scope of this paper, both wastewater recycling and the energy efficiency of wastewater treatment plants are associated with the reuse of resources, which are characteristic of level 4 interventions (see, for example, [17–20]).
  Attention should be paid to the fact that the reuse and recycling of wastewater are generally considered energy intensive (as described in Section 1), which can mischaracterize these processes as alternative technologies for enabling energy efficiency and conservation. The typical analysis of a WSS energy lifecycle considers the energy intensities of the chemicals used in water treatment in addition to the materials and components of the physical systems (e.g., pipes). Energy analyses considering lifecycle assessments of WSSs are presented, among others, by Lundin and Morisson [21], Filion et al. [22], Racoviceanu et al. [9], and Stokes and Horvath [23].
- Level 5, discussion of the center/periphery relations: in the context of water supply, level 5interventions can be obtained, for example, through the decentralization of supply and incentives toward the enhanced use and management of local water sources in the form of distributed water infrastructures [24,25]. Physically, the center/periphery relationship influences the energy efficiency of a WSS once the relative position between the water sources, the treatment plants and the consumers influences the amount of energy needed for water transport as well the head losses along the network and water mains. Filion [26], for example, describes the influence of city shape on the energy consumption of water distribution systems. Level 5 interventions are strongly related to urban planning and zoning and can be effectively implemented through proper and optimized system designs. This occurs because the location of natural water sources (e.g., rivers, springs) cannot be changed, and the layout of water mains and the distribution networks depend on the local topography and other types of infrastructure (mainly the streets and roads).
- Level 6, changes in ethical and esthetic paradigms: level 6 involves changes in opinions, consumer choices and consumer behavior and, therefore, represents the most difficult energy efficiency action that can be implemented.

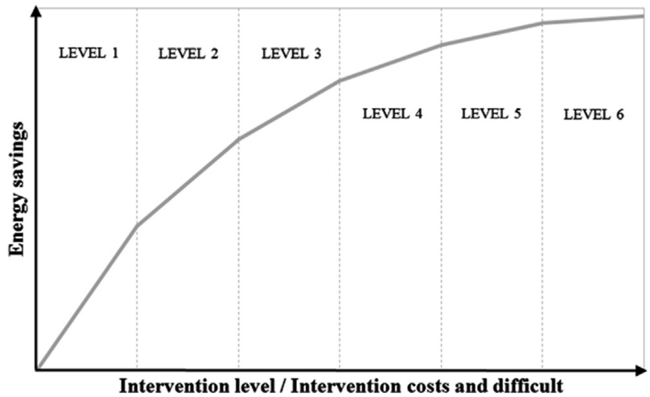

Fig. 2. The relationship between the energy efficiency intervention level, its cost and difficulty, as well as the cumulative energy savings.

Examples of level 6 interventions in the context of WSSs are presented in the paper by Proença et al. [27], who evaluated the potential for energy savings through water conservation measures undertaken by end users (residential, commercial and public). In the case study carried out by Proença et al. [27], a reduction of 0.5% in the total consumption of electricity in the city of Florianópolis (Brazil) was demonstrated to be possible from the use of dual-flush toilets, greywater reuse and rainwater catchment. Level 6 interventions are outside the scope of the present work.

The energy saving impact of each intervention level can be associated with the specific intervention's difficulty and/or cost of deployment. This non-linear relationship ideally grows and asymptotically tends to the maximum energy saving potential; that is, when applying the above interventions by following the levels in ascending order, the closer that the interventions move toward the higher-levels, then the greater that the difficulty and/or implementation cost become. Further, in this manner, the cumulative energy savings are present in continuously decreasing increments. This model is shown in Fig. 2, in which all of the levels were denoted with the same dimension for the purpose of illustration because it is very difficult to establish the actual dimensionality of a level.

Although in past decades the use of hydropower was the most evident relation between water and energy, today the focus of this relationship has turned to the role of water as a consumer of electricity, which has turned water distribution into an important stage in terms of the consumption and use of energy [28]. According to Frijns et al. [29], the high consumption of energy affects water industries around the world, been associated with climate change issues.

In this paper, three basic dimensions in which the use of electricity in CWSSs can be evaluated were identified, including (1) the project and design dimension, (2) the operational dimension and (3) the physical dimension (which is related to the equipment, the structures and the components used as well as their repair and maintenance).

The design of water distribution systems is a broad and open problem in hydraulic engineering, involving the insertion of new elements into the system, the rehabilitation or replacement of existing elements and the decisions regarding operation, reliability and security [30].

The classical methods for the design of water distribution networks are based on an iterative process of trial and error, which is used to define the pipe diameters in each section to meet the various required levels of pressure and flow [31]. Such methods do not consider, however, the optimum combination of the network and pumps necessary to minimize the investment costs (implementation of the structure and equipment) and operational costs (energy consumed by pumping) [31]. Thus, explorations of the pipe diameters that meet the required hydraulic loads with lower costs play a major role in the design of water distribution networks [32].

The mathematical problem of the operation of water supply systems involves discrete and continuous decisions as well as the complexity caused by closed-loop networks and temporal coupling throughout the entire planning horizon [33]. Carrijo and Reis [34] state that the cost of electricity is the most relevant parameter in terms of the operational optimization of water supply systems with respect to minimizing the operating costs. Despite that, operational rules are used to ensure the continuity of public supplies without regarding the energy savings in the operated motors [35,36].

In the physical dimension, defining the type of pump that best meets the water demand under a required specific pressure head is a major problem in the design of water distribution networks [37].

The main problems that compromise the energy efficiency of motor-pump sets used in CWSSs include oversizing for taking into account uncertainties concerning the deterioration or growth of the system, the regulation of flow through bypasses and valves, operation out of the maximum efficiency point [38], inefficient pumps and motors, cavitation [39,3], excessive vibrations in shafts and housings, overheating of the engine bearings and windings, widespread leaks in pumps, and wear and corrosion on the impellers and casings [3]. It is important to note that some of the physical dimension problems, such as flow regulation and operation out of the maximum efficiency point, are closely related to the operational dimension.

In many communities, the consumption of energy during water pumping is the largest component of operational supply costs, and the energy wasted in leakage compensation is associated with different environmental impacts, such as greenhouse gases, acid rain and the depletion of resources [40]. The magnitude of this problem is proportional to the high water loss rates in water supply systems, which reach between 30% and 40% worldwide [41,42].

In addition to the energy content added to the volumes of lost water, Colombo and Karney [40] emphasize that leakages result in the use of oversized motor-pump sets to compensate for the additional requirements of flow and pressure, producing proportional energy waste.

Water loss problems are related to the three dimensions of analysis proposed in this research. The design and operation dimensions are responsible for setting the topographic water levels, the operational limits and the resulting pressures for the various sectors of a network; these dimensions are also responsible for the type of material, the pipe layout and the accessories characteristics (physical dimension) that make the network more susceptible to leakages. The operation of the system, in turn, plays a key role in pressure and leakage flow management.

The main alternatives for energy and hydraulic efficiency in CWSSs, which were obtained from an extensive literature review, are presented below.

3.1. *The use of renewable energy sources for pumping*

The use of renewable sources of energy (especially wind and solar) for water pumping was considered in several studies [43–50].

Wind systems, whose turbines provide direct shaft power to the pumps, have been used to pump water on a small-scale for years, especially in agricultural or remote areas [46]. The results from Velasco et al. [44] and Lara et al. [50] have identified the preferential use of wind power generators to supply the electric power to conventional motor-pump sets based on the attractiveness of this alternative in comparison to large pumping systems in which the physical

arrangement of the stations impedes the direct coupling of the wind turbine with the pump.

Ramos and Ramos [48] and Bueno and Carta [51] support the widespread use of wind power for large-scale pumping, which indicates the feasibility of using such technology in CWSSs. Purohit [47] suggests that the unit cost of water pumped by wind power is highly variable, depending on the wind potential of the site and the design parameters of the system.

Vilela and Fraidenraich [52], Mahmoud and el Nather [53], Odeh et al. [54], Ghoneim [55], Glasnovic and Margeta [56] and Ould-Amrouche et al. [57] evaluated the use of photovoltaic systems (PSs) for water pumping; in particular, they investigated the use of water pumping for urban supply and irrigation. As in the case of the wind systems, the PSs are studied mainly for small-scale pumping applications in rural and remote areas.

Ould-Amrouche et al. [57] also state that the use of 1000 PSs associated with 1 kW pumps can prevent the emission of 4.2 t of CO_2 per year in comparison to internal combustion engines burning diesel oil. The authors consider PSs more costly in terms of investment, with lower costs per volume of water pumped in comparison with diesel-based systems. This conclusion confirms that given by Mahmoud and el Nather [53].

Due to the high initial cost, Odeh et al. [54] mention that the use of PSs for water pumping systems has been limited to medium-scale systems (11 kW or less). For attractiveness rates up to 20%, the authors consider the PSs advantageous over systems that use internal combustion engines. Moreover, the pump head is directly proportional to the unitary cost of water pumped, and this variable (the pump head) is also highlighted by Ghoneim [55]. Ghoneim [55] suggests that reductions in the cost of wind and photovoltaic equipment due to technological advancement, the development of domestic enterprises for the production of equipment and increased demand will allow these alternatives to become economically feasible for WSS pumping in the medium and long term.

The use of wind, solar and hydro hybrid systems in pumped-storage systems is described by Ramos and Ramos [48] and Vieira and Ramos [58] as a major technological alternative for the reduction of uncertainty, which is inherent to both pure wind and pure solar pumping systems. These storage systems are analogous to reversible hydropower plants, which consist of upstream and downstream reservoirs interconnected by hydropower and pumping systems. Water is pumped to the upper reservoir during the electric off-peak periods and is passed into the turbine to the downstream reservoir in the electric peak periods [58]; alternatively, the water can be pumped in accordance with an optimized operation schedule.

3.2. Hydropower recovery

The hydropower potential of water supply systems has been known for a long time; however, it has not been adequately explored worldwide. Cases of micro turbines used for power generation in water supply systems have been reported in the literature (e.g., [29]). Systems installed in areas with high topographic gradients, in which water is transported by gravity, tend to offer high pressures in the water mains and distribution networks, making these systems capable of hydroelectric power generation.

In addition to generating electricity, turbines installed in water distribution networks can act as pressure control systems, replacing the pressure reducing valves (PRVs), which are important tools in the management of water losses/leakages [48,42]. While PRVs reduce the pressure through the dissipation of energy, water turbines can convert this excess pressure into useful electricity [59,42].

The main benefits of hydraulic energy recovery in WWSs, according to Vieira and Ramos [58], include increases in the energy efficiency of the system through the use of local sources and decreases in the dependence on external/grid energy; additionally, hydraulic energy recovery favors overall reduced operational costs. Vieira and Ramos [58] also emphasize that the implementation of small hydro plants in WSSs presents a considerably reduced implementation cost because many of the necessary components are already present in typical WWSs.

3.3. The management of pressure and water losses

"Water losses" are technically identified as leakages or structural problems in reservoirs, as non-physical losses represented by billing and metering errors and as a synonym to leakages in pipes and distribution networks. The final definition is accepted as the most adequate for the present paper in consideration that such losses are, in general, the major types that occur in WSSs.

According to Ulanicki et al. [60], the use of pressure control is a cost-effective measure to reduce leakages in water distribution systems. According to the authors, in addition to reducing the existing leaks and preventing the emergence of new leaks, pressure management reduces the incidence of pipeline ruptures, avoiding the associated repair costs as well as the disruption of traffic on public roads and the supply of water to the customers.

Leakages are considered to be pressure-driven demands in the hydraulic analysis and modeling of water losses [61,28]. The relationship between pressure and leakage compromises the demand management and the conventional modeling of distribution networks, which requires a much larger amount of data and a significant research effort for a full understanding of the hydraulic behavior of these networks in real situations. All of these requirements are in addition to the usual sources of information, such as telemetry, water bills and water meters [62]. The real leakage flows are usually unknown, and the nodal demands modeled without considering these flows may result in errors in pressure determination [63].

According to Cabrera et al. [28], leakages can be modeled as energy leaving the control volume, which is analogous to the hydraulic power supplied to consumers in the form of the network pressure. Effective pressure management is almost always part of the management strategy for water losses: while it is possible to reduce leakage flows by reducing network pressures, this strategy must consider the maintenance of sufficient nodal pressures to meet the real water demands of the consumers [42].

Araujo et al. [41] and Nicolini et al. [64] indicate that the use of devices, such as pressure-reducing valves (PRVs) in particular, to increase the head losses in the network is the most frequently used technology for pressure management and leakage reduction. The use of PRVs may seem paradoxical in relation to the energy efficiency of the system because the incorporation of minor head losses is considered a goal during the design of networks and pipelines. Some initial challenges to the successful use of PRVs are the quantification and positioning of valves in the network to produce the desired effects and the simultaneous maintenance of the operational pressure limits at adequate levels.

The optimal positioning and quantification of PRVs can be accomplished by hydraulic simulation in association with the use of optimization techniques, such as genetic algorithms [41,65]. The use of genetic algorithms to locate and determine the optimal operation of VRPs has been the focus of several scientific studies [64].

Ulanicki et al. [60] evaluated predictive pressure control strategies based on demand forecasting, hydraulic modeling/simulation and a feedback strategy in which the system pressure is adjusted against an optimal pressure-flow curve for the control area, which is based on continuous pressure measurements. In the cases studied, leakage reductions as high as 50% were found.

Assuming that it is impossible to totally eliminate leakages in water distribution networks [66,67], it is essential to use corrective

actions in addition to management techniques based on pressure control. According to Li et al. [68], the main issues involved in controlling leaks are (1) the rapid and effective detection of leakages, (2) the prediction and assessment of leakage probability in different zones of the network, (3) the classification and management of these zones within the system as a whole, and (4) the management of measurement instruments and the use of such data for system optimization.

The detection and location of existing non-visible leakages typically occur through the use of acoustic instrumentation, which interprets the noise generated by the leakages [69,70]. Examples of acoustic detection equipment include listening aquaphones (used in direct contact with pipes and hydro-mechanical components), ground microphones for locating noises associated with buried pipes and state-of-the-art leakage noise correlators [71].

A question is raised regarding the significant percentage of water that is still lost in the majority of the water supply systems around the world, despite the fact that the water loss problems and the methods and technologies to combat water loss are widely disseminated in the literature and currently dominated by engineering efforts. The literature points that the answer to this question is strongly related to the cost/benefit ratio of eliminating leakages (especially the replacement and/or repair of pipes alone), that is not attractive to managers of systems from a strictly financial point of view. Because a zero water leakage rate is not a plausible goal, the concept of Economic Level of Leakage (ELL) has been defined as the point at which the marginal cost of active leakage control equals the marginal cost of the water [67]. According to Venkatesh [67], the rehabilitation of pipes is rarely performed for the sole purpose of eliminating leakages; additionally, issues such as the reliability and the improvement of water quality are difficult to assess and demand a holistic analysis of costs and benefits. This paradigm shift in light of the definition of ELLs occurs through the evolution of a purely financial concept into another, which considers the environmental and social aspects and was first reported by Ashton and Hope [72], for whom the lack of consensus on environmental valuation techniques is a strong barrier to their incorporation in the accounting process during the calculation of ELLs.

As mentioned in Section 3.2, a more energy efficient means of reducing pressures in a water network is to use hydraulic turbines instead of PRVs. Hydraulic turbines can convert excess pressure into useful hydropower, instead of dissipating the energy by increasing the head losses, which is the result of PRV use.

3.4. Operational optimization

Conceptually, the operational optimization problem of a CWSS, when focused on energy management and conservation, aims to minimize the energy consumption and demand; the minimization process is subject to operational limits and service levels in supplying demands with the minimum required pressure levels, while considering the system's spatial and temporal operational scales.

Burgschweiger et al. [33] consider the reduction of costs associated with electricity as the primary operational goal of WSSs given the relevance of electricity in business accounting. They also describe the difficulties of modeling the problem of operational optimization of WSSs because modeling involves both discrete and continuous decisions in addition to the complexity due to the incorporation of closed-loop networks and temporal coupling throughout the planning horizon.

One advantage of operational optimization over other hydraulic and energetic efficiency measures is that it is not a structural intervention, hence it may be deployed in general without the need for large investments. Additionally, the economic benefits from operational optimization are realized in the short term [35,36].

The operational optimization of WSSs can be performed through four steps, including (1) establishing the definition of the optimization problem (the objective function), (2) carrying out the computational modeling of the system, (3) calibrating and validating the hydraulic model, and (4) performing the simulation and optimization procedures.

The objective function of the operational optimization problem of WSSs can assume various forms. For example, the objective can be to maintain the minimum pressure on the network or to minimize the pumping costs through the use of pumps with variable speeds [73]. Alternatively, the objective can be to minimize leakages by the optimal control of reduction valves [74,75] or to adjust the flow rates and pressures offered to consumers through pump operations [76]. Further objectives include the minimization of water losses through pressure control by defining the optimal levels of reservoirs [63] or the minimization of the cost of pumping energy by using the best combination of multiple operating motor-pump sets [35,36]. The final example is to maximize energy efficiency of a supply system that uses water and wind turbines for power generation [77,78].

The modeling step consists of formulating the system in a discrete computational interface, which allows the components and the hydraulic behavior of the system to be represented in a simplified form. For this, data are needed regarding the physical structure of the system, such as the pump curves, the diameters and roughness of the pipes, as well as the geometric characteristics of the network (the layout of pipes and the topographic elevations). The hydraulic models briefly described in Section 3.8 of this article "[…] are widely used for analyzing the behavior of the system under different scenarios, but a reliable prediction may only be achieved with the calibrated model" [64].

The hydraulic models are calibrated by comparing the model results with observed values. This step is followed by adjusting the parameters (e.g., the pipes roughness and the spatial distribution of demands) to minimize the difference between the modeled (simulated) and measured (observed) results [79]. After calibration, the model can be validated by comparing its results with an observed data set, one which was not used during the calibration; additionally, the comparison can be carried out under different systems conditions.

Once calibrated and validated, the hydraulic model can be coupled to an optimization module, which uses computational optimization techniques (for example, genetic algorithms) [35,36,63] to search for the optimal solution of a given objective function.

The optimization approach described assumes that the operational characteristics of the system over time are known; that is, the optimal value of the objective function is obtained for a particular temporal pattern of hydraulic parameters, especially water demand. The knowledge of water demands (generally on an hourly basis) is considered by Herrera et al. [80] as a key factor for the application of hydraulic models aimed at increasing the energy efficiency of WSSs through operational optimization.

A different approach considers the real time operational optimization. Through the use of hydraulic monitoring systems (which measure the flow rates, pressures and water levels) at representative points of the system and their association with supervisory and control systems, components such as pumps and valves can be operated according to the system's hydraulic and energetic behavior, which is based on pre-established operational limits. This approach is proposed by Campisano et al. [81] to reduce leakage through the use of real time valve operation. Giacomello et al. [82] suggested a hybrid method of integrating the linear programming with a Greedy Algorithm for real-time pump scheduling, which was aimed to reduce energy costs. After testing the model both in a benchmark and in a real system, Giacomello et al. [82] concluded that the proposed hybrid

algorithm was more efficient in finding the optimal solution than genetic algorithm, which is commonly used for the operational optimization of WSSs.

Whatever approach is taken, the importance of hydraulic and energetic monitoring of a WSS to generate data and characterize the spatial–temporal patterns of its main variables is evident. Ideally, monitoring should go beyond the basic measurement systems of WSSs, which involves the hydraulic and electric motor-pump set parameters and the macro-measurement of flow and reservoir levels in water treatment plants, all of which tend to be manually recorded, particularly in developing countries. The ideal cited monitoring involves, in addition to the basic measures, reaching a level of real-time telemetric monitoring of hydraulic parameters at strategic points within the distribution system, which are the so-called district metered areas considered, for example, in Tabesh et al. [83].

3.5. The use of efficient motor-pump sets

Kaya et al. [39] claim that 30% of the energy consumed by hydraulic pumps can be avoided through the use of better designs and the selection of appropriate equipment. According to the authors, the maximum efficiency point of a pump can be achieved by using the correct selection/design and according to the working conditions and the system design.

With respect to pumps, the use of oversized motors for operating under critical load situations is another significant source of waste because this approach generally shifts the machine operation into less efficient regions [39]. The highest efficiency points of electrical motors are located in the region of the efficiency curve in excess of 75% of the maximum load. According to Kaya et al. [39], motor efficiencies vary from 70% to 96%, and high-efficiency motors must be prioritized during selection and acquisition.

According to de la Torre [84], parameters such as the specific speed, the suction specific speed and the net positive suction head (NPSH) influence not only the selection of more efficient centrifugal pumps but also the maintenance of these levels of efficiency and the reduction of repair periods during the equipment lifetime.

The specific speed is a dimensionless parameter, which defines the geometry of the pump impeller (all impellers with the same geometry have the same specific rotation, regardless of size). According to de la Torre [84], the specific speed associates the discharge with the speed and the head that the impeller is capable of providing. This definition considers each impeller vane at the best efficiency point. The author also comments on the importance of this parameter in association with energy efficiency.

The primary influence of the specific speed on the hydraulic behavior of a pump occurs in the efficiency curve shape (the curve flattens with decreasing specific speed), which is an important factor for the control of the equipment. According to de la Torre [84], the optimal efficiency of a centrifugal pump occurs for a specific speed of 34. At the same specific speed, volute pumps with rotors tend to be more efficient than diffusion pumps.

The suction specific speed is another dimensionless parameter. In particular, it expresses the flow capacity of the pump suction, connecting the flow in each impeller passage to the required NPSH at 3% head losses ($NPSH_{R3\%}$), where both are at the point of best efficiency. This parameter depends on the geometry of the impeller and the aperture size. From de la Torre [84], the limit of suction specific speed for water is 185 (with units in the International System), and values above 185 can cause cavitation. For suction specific speeds less than 185, the NPSHR curve tends to be flatter with a more favorable range of values. In the case of values above this reference, the NPSHR at the best efficiency point tends to be lower but will increase quickly at other operating points.

The net positive suction head (NPSH) is the difference between the total absolute pressure in the suction flange of the pump and the steam pressure of the liquid in question and is expressed in meters [84]. It is divided into the available NPSH ($NPSH_A$), which represents the pressure head in the pump suction provided by the installation in question, and the required NPSH ($NPSH_R$), which is the lower suction pressure under which cavitation occurs. De la Torre [84] recommends that the $NPSH_A$ must be 1.5 to 2.0 times the $NPSH_{R3\%}$ so that the life of the impeller reaches 40,000 h without suffering erosion by cavitation, pressure drop, vibration or noise. The $NPSH_{R3\%}$ is obtained in associating with a 3% head loss according to the $NPSH_R$ calculation. According to the NBR 12.214 standard [85], the $NPSH_A$ should be 20% or at least 0.5 m above the $NPSH_R$.

Another relevant observation from to de la Torre [84] considers the use of higher capacity pumps in comparison to smaller machines. It is known that the performance of a centrifugal pump tends to increase directly with the size/capacity, which provides an energy advantage over the use of several smaller pumps. Moreover, the use of multiple sets of smaller motor-pumps provides more flexibility to a given operating station, particularly when there is significant variation in the flow. Therefore, both cases must be considered when selecting pumps in light of energy efficiency constraints; further, the cases can even be used together.

Kaya et al. [39] suggest that pumps operating at flow rates below 40% of the nominal value have increased levels of vibration, noise and radial loads in addition to a significant decrease in efficiency. During the lifetime of the pump, it is possible to achieve an increase in the efficiency through the elimination of roughness and crusts, which occur as a result of material aging [39].

Labeling programs, which provide a basis for energy efficiency comparisons between various equipment types (including pumps and motors), are key initiatives for increasing the hydraulic and energetic performance of pumping systems. Saidur [86] presents a summary of the Mandatory Energy Performance Standards (MEPS) for motors, which establishes standards for the energy performance of these products. The summary of this standard, as analyzed by the author, is presented below: USA Energy Policy Act – EPAct (1992); USA Energy Policy Act – EPAct (1992), Canada's Energy-Efficiency Act (EEAct) (1992), which is very similar to EPAct; Mexico's NOM-016-ENER-2002, with similar indexes as that of EPAct, Brazil considers NEMA12-9, according to the Brazilian Labeling Program [87]; CEMEP European Union [88], Australia's Energy Performance Program - MEPS (AS 1359.5:2004).

The labeling and determination of minimum energy efficiency levels for pumps are also under development. In Europe, for example, actions have been taken in this direction through the European Association of Pump Manufacturers [89] and by the European Union based on studies within the Ecodesign Directive [90].

3.6. The use of variable speed motor-pump sets

The flow variation in pumping systems may occur as a result of several situations, such as the need to turn pumps on only when required (partial load operation), the use of a by-pass to return a portion of the pumped flow to the suction tank, the use of a suction tank with a variable level, the insertion of head losses in the system through the throttling of control valves, changes in the rotation of the pump by hydraulic or electrical coupling between the pump and engine, the use of pumps operating in parallel, or the use of inverters in the engines [39].

According to Gibson [91], variable-speed drives (VSD) are an energy-efficient alternative for controlling pump flows and can be used similar to traditional options, such as the throttling of valves. According to the author, the effectiveness of VSDs on flow control depends on the interaction between the pump characteristic curve

(head x discharge) and the process/system curve. This includes the use of the magnitude of required speed variation to obtain the maximum and minimum required flow rates in addition to the unstable regions in the pump curve, which are usually located in the range below 35% of the nominal flow. Thus, the selection of pumps with curves suitable for speed control should be considered in projects that seek to optimize the energy efficiency of the system.

3.7. Optimization of the storage capacity and the reservoir operation

Significant cost reductions in water supply systems can be obtained by optimizing the storage capacity of reservoirs in conjunction with the optimal control of pumping stations with variable electricity rates [92]. According to Fang et al. [92], the optimal operation of distribution systems with multiple water storage reservoirs and multiple sources is a large-scale nonlinear optimization problem with continuous and discrete variables; apparently, this problem is also difficult to solve.

The use of water storage can minimize pumping requirements during peak demand periods for electric power [93], and this approach constitutes a common practice when energy prices vary over time. Despite the importance of tanks for the efficient operation of WSSs, including their positive impact on energy efficiency, there are few models specifically targeted to identify optimized designs of distribution networks that include tanks [94]. According to Batchabani and Fuamba [94], the genetic algorithm technique is the preferred approach in modeling and optimizing this type of problem today.

The model of operating rules for reservoirs proposed by Fang et al. [92] consists of maintaining the tank level as high as possible during off-peak periods and removing the reservoir inflow during the peak period. If a drawdown to the minimum operational level occurs, water is supplied to maintain this level until the peak period ends.

Vamvakeridou-Lyroudia et al. [95] developed an investigation on the design of water distribution networks in which reservoirs and their physical and operational characteristics are considered as decision variables in an optimization problem; their study approaches the analysis with the use of genetic algorithms. The simulation considered the daily operational pattern of a classical system from literature and proposed an engineer-oriented approach, which considers the tanks (and their hydraulic and operational characteristics) to be decision variables in the network design.

The pump-storage reservoir in association with hydro-turbines offers a operational alternative for the management of water demand, allowing for the generation of renewable energy from water supply systems and taking advantage of a significant fraction of the existing structure (tanks, pipes, etc.). According to Vieira and Ramos [58], in addition to guaranteeing continuous flow during daily operation, the adaptation of water supply systems to this alternative reduces the external energy dependence and the operational costs.

3.8. Optimized pipe and network designs

The optimal design of water distribution systems is a widely explored research area, which still faces many barriers and practical challenges [96], such as the difficulty in defining the objective functions and constraints, the variability of flow in the network, the design optimization difficulties related to the fact that these systems are not typically constructed at once, and the fact that solutions of optimization problems directed at cost minimization often lead to under-sized networks.

Composed of pipes, pumps, valves and other components, the water distribution networks are modeled and simulated based on the laws of mass conservation (the hydraulic balance between the provided and consumed flows) and energy conservation (which relates the hydraulic heads and losses over the network). The flows in these laws are governed by complex, non-linear, non-convex and discontinuous hydraulic equations [97].

The classical and extensively described model of water distribution network design optimization has as an objective function the minimization of network deployment costs, which are used to define the smallest pipe diameters that meet the hydraulic requirements in terms of the pressures and flows [97–104,32]. Some methodologies, such as those presented by Gomes and Silva [31] and Prasad [105], consider the minimization of the total system costs over the system lifetime, which involves the installation costs (costs of pipes, pumps and accessories) and the operational costs (mainly energy).

In this context, the energy efficiency of the system is analyzed as a secondary issue, and any reduction in the energy used occurs as a result of the minimization of operational costs (pumping energy, mainly). That is, the optimization process determines the optimum economic condition of the system, which in most cases is not equal to its optimum condition in terms of energy use.

Walski [106] criticized the use of optimization techniques for the design of water distribution networks aimed simply to minimize the associated costs. For this author, the design of water distribution networks is a multiobjective problem, and the objective function to "minimize the costs" should be replaced by another likely function to "maximize the benefits of the network." Walski [106] asserts that one of the problems associated with the implementation of this new paradigm is the definition of network benefits (e.g., increased capacity), which in practice can be established with the aid of designers and skilled operators.

In practice, the optimum design of a water distribution network is accomplished through the coupling of two modules, including (1) the optimization module, which is composed of algorithms responsible for determining the optimal solution of the objective function (minimization of the investment or operating costs, for example), and (2) the hydraulic simulation module, which is responsible for the simulation of system conditions based on mass and energy balances and the determination of the hydraulic characteristics associated with the constraints of the optimization problem (the demands, pressures, and head losses along the network analyzed in the temporal and spatial scales). One of the most commonly used and tested hydraulic simulation modules in the world is the EPANET [107], which is distributed by the United States Environmental Protection Agency (EPA) and is accepted by the scientific community and engineers responsible for modeling WSSs.

The proposed techniques for the optimum design of WSSs vary from linear and non-linear programming methods to variations in evolutionary algorithms and heuristics. Table 2 presents a summary of several studies conducted on pipe and network system design optimization.

4. Analysis of the opportunities for energy efficiency and hydraulic improvements in CWSSs

After reviewing the relevant literature, several technological alternatives for energy and hydraulic improvements in CWSSs were identified, further revealing that some are more promising than others. Hence, a consistency analysis must be performed to identify the real opportunities.

Storage capacity optimization is an alternative that presents significant potential for exploitation, especially in a climate change

Table 2
A summary of the optimization methods applied to pipe and network design.

Author	Proposed method	Objective function	Main results and conclusions
Gupta et al. [98]	Genetic algorithms	Minimize the network investment cost	Genetic algorithms performed better solutions for medium size networks in comparison with non-linear programming
Afshar et al. [108]	General purpose optimization package (DOT) combined with an floating algorithm	Minimize the network investment cost, considering the system reliability	In two steps, the method defines the optimal size of a network of pipes followed by the best (lowest cost) possible arrangement of pipes based on the network reliability.
Keedwell and Khu [97]	Hybrid genetic algorithm with cellular automata	Minimize the network investment cost	The proposed method outperforms the conventional non heuristic-based genetic algorithms, producing more economically designed water distribution networks
Gomes and Silva [31]	Non-linear programming (Gradiente Reduzido Generalizado)	Minimize total cost (sum of investment cost and pumping energy cost)	The effects of parameter variations on the operating conditions of the project should be considered in the methods of the economic design of water supply systems
Samani and Mottaghi [99]	Integer linear programming	Minimize the network investment cost	The choice of the decision variables is crucial in the initial performance of this technique, which tends to converge quickly to the optimal solution when the choice is well made.
Zecchin et al. [100]	Ant colony optimization based algorithms	Minimize the network investment cost.	An additional mechanism offered by the Max–Min Ant System technique, effective in improving the performance of the algorithms of a conventional ant colony
Bai et al. [109]	Combined quadric orthogonal circumrotation regression design, quadratic programming and linear programming	Minimize annual cost	Each of the techniques was applied to solve specific parts of the problem (the optimal diameter, the optimal distribution of flows and the minimum cost of pumping), allowing the methodology to be applied in both systems with pumping or by gravity
Vamvakeridou-Lyroudia et al. [95]	Multiobjective genetic algorithm	The target is to minimize construction and energy costs	The paper proposed an “engineering oriented” approach to the simulation of tanks as decision variables for water distribution system design optimization, considering capacity and minimum operational volume as decision variables, and omitting risers. The shape and ratio between emergency/total capacities were taken into consideration as design parameters
Chu et al. [101]	Modified Immune algorithm	Minimize the network investment cost	The immune algorithm identifies the optimal solutions with significantly fewer evaluations than genetic algorithms or others. Integrating an immune algorithm with a genetic algorithm increases the optimization performance
di Pierro et al. [96]	Multiobjective hybrid algorithms (ParEGO and LEMMO)	Minimize the total cost and head deficit	LEMMO is a good technique for complex network design problems in which time or financial considerations allow for a limited number of hydraulic simulations to be performed. ParEGO can be successfully applied to reduce the number of expensive simulations in small or medium scale networks
Baños et al. [102]	Memetic algorithm	Minimize the network investment cost	The meta-heuristic methods used performed well in medium size networks, but a greater computational effort was needed to obtain the most accurate results in large-scale networks
Bolognesi et al. [103]	Genetic Heritage Evolution by Stochastic Transmission algorithm	Minimize the network investment cost	The technique performed similar to other studies on the optimization of small networks and provided superior performance in optimizing large networks
Cisty [104]	Combined genetic algorithm and linear programming method (GALP)	Minimize the network investment cost	The aggregation of the linear programming module to the genetic algorithm effectively bypassed some limitations of this technique, as described by the author
Mohan and Babu [32]	Honey-bee mating optimization	Minimize the network investment cost	Honey-bee mating optimization identifies the optimal solution with fewer evaluations or iterations in comparison with genetic algorithms, simulated annealing and the shuffled frog leaping algorithm
Montalvo et al. [30]	Multiobjective particle swarm optimization	Minimize the network investment cost, minimize the lack of pressure in nodes, and minimize costs of the water not delivered due to disruptions in the system and associated repair costs	The authors highlight the importance of integrating the search ability of the algorithms with the experience of experts because the proposed method is based in a computer–human integrated system to obtain the global optimum, not a local optimum
Prasad [105]	Genetic algorithm	Minimize total cost (sum of investment cost and energy cost)	The technique resulted in optimal solutions with lower costs in comparison to the results of other researchers
Wu et al. [110]	Multiobjective genetic algorithm	Minimize total economic cost of the system and greenhouse gas emissions of the system	The paper considered the use of variable-speed pumping during the optimization of network design for the reduction of total costs and GHG emissions and concluded that variable-speed pumps are effective for achieving the multiple objectives

scenario. In certain regions, the possibility of changes in hydrological patterns may cause scarcity in areas that currently have sufficient water availability. Although present in WSSs project standards worldwide, the storage capacity is usually defined based on static scenarios of consumption and on projections of population growth in association with the hydrological behavior of the considered watersheds. Assuming that hydrological variability is caused by climate change, the design criteria of the WSSs must take into account these hydrological uncertainties, which suggest water storage to be a key technological alternative for climate change adaptation.

The use of variable speed motor-pump sets, which is a well known classical alternative in hydraulics literature, is still rarely used in WSSs, especially in developing countries. In addition to allowing variable pumped discharge in a more efficient manner than the use of valves and by-passes, the use of variable speed drives in association with control and monitoring systems allows the motor-pump sets to continue to operate near their best efficiency points.

Garcia et al. [87], Saidur and Mahlia [111] and Hasanuzzaman et al. [112] reported considerable savings gained from the use of high efficiency motors; these reports were given in a general context and not specifically for that of water supply.

Hydraulic energy recovery is an interesting alternative to gravity water supply systems, allowing for energy self-generation and greater energy independence in relation to the regional and local grids. Although this approach is also a classical technology type in hydraulic studies, including the maturity of technology with respect to small-scale hydro generators, only a few researchers have considered this alternative in the specific context of WSSs.

The recovery of hydropower in CWSSs is highly variable according to the local potential (which is usually defined by the topography and the relative position between the water source and other system components) as well as the layout of the system. Because of this variability, the hydropower recovery potential can be barely sufficient to reduce the electricity consumption of the local network or to make the supply system energetically self-sufficient, with the possibility of selling the excess energy generated. Kucukali [113,114], for example, analyzed the potential of hydropower recovery in 45 dams used for municipal water supply in Turkey, concluding that this set of dams could produce 173 GWh year^{-1} of electric energy without environmental impacts, once all structures (associated with water supply) were erected.

It is difficult to estimate reference values for calculating the energy savings with the use of renewable sources for pumping. The potential for energy conservation with this alternative, as well as the recovery of hydraulic energy, is highly variable depending on the local potential.

Directly or indirectly, most hydraulic and energy efficiency alternatives identified in this paper converge to a single solution, which is the correct definition of pressure and water levels in the system, both in design or operational dimension. In association with the optimized pressure and water losses management, the system operation must be a prioritized alternative for energy and hydraulic efficiency in CWSSs; this is a requirement so that it can be deployed without the need of large investments and structural/physical changes. It is important to note that some of the alternatives described in the paper, such as tank operation and the use of variable-speed motor-pump sets, are commonly associated with operational optimization, which can maximize their individual impacts over the system's energy efficiency.

Several optimization techniques, which have been tested and validated in the literature, also can be applied to improve the design of water distribution systems. Most studies, however, disregard the system's operational conditions and costs, further ignoring the energetic optimal conditions because they simply seek to define the optimal solutions in terms of investment costs. Thus, this is a promising area for future research with a focus on multiobjective optimization techniques to carry out simultaneous energetic and economic objectives.

Pressure and water loss management has been studied for a long time. Nevertheless, water losses by leakage likely remain the main source of wasted water and electricity in WSSs. Although the necessary technologies and methodologies to solve water loss problems are known and available, the cost of implantation inhibits problem mitigation. Most of the identified opportunities for energy and hydraulic efficiency require hydraulic and energetic data and information, which ideally should be monitored continuously and at various sites throughout the system.

System managers should be aware of the importance of system monitoring, which is not a reality in many CWSSs, particularly in developing countries. Marunga et al. [115] monitored flow and

Table 3
The estimated energy savings in water supply systems (adapted from XENERGY [118] apud Brasil [117]).

Energy efficiency action	Energy savings
Reduction of required energy	
The use of tanks for flow control and storage	10–20% Savings
The elimination of bypass loops and other unnecessary flows	
Increased pipe diameters	5–20% savings, but with high associated costs
Reductions in oversizing design parameter limits for defining the system capacity	5–10% Savings
Correct pump design based on the loads	
Correct pump sizing	Pumps generally present an average 15–25% oversizing
Reduced or controlled pump speed	
The use of variable speed drives instead of valves	30–80% Savings, applicable to high variable head systems
The use of more efficient equipment	
The substitution of actual pumps for a most efficient or with best efficient operation point compatible with the systems operation point	16% of pumps generally have more than 20 years of use, and the system's operation point is variable over time, so the original best efficient point is not the same as when the system was designed. The efficiency can decrease from 10% to 25%. Modern pumps are 2% to 5% more efficient than older ones. Energy savings can vary from 2% to 10%
The replacement of belts by direct coupling	1% Savings
Operation and maintenance	
The replacement of worn impellers. Checking the bearings, the mechanical seals and other seals	1–6% Savings

pressure parameters in a sector of the water distribution network of the city of Mutare (Zimbabwe) to quantify the effects of reducing pressure by using PRVs over leakage rates. The authors modeled the hydraulic system with EPANET to establish the limits of pressure change by maintaining minimum allowable pressures at all points of the network. In the monitoring process, the pressure measurement points ranged between 77 m to 30 m through the operation of the PRV. Marunga et al. [115] found that a 35% reduction in pressure resulted in a 25% reduction in leakage rates.

Girard and Stewart [116] presented the results of a pressure and leakage management (PLM) system in a trial area located on the Gold Coast (Queensland/Australia). The field PLM experiment developed in the Gold Coast included leakage detection, pressure reduction by PRV and flow modulation, resulting in a measured reduction of the minimum night flow from 6.2 $l.s^{-1}$ to 3.25 $l.s^{-1}$ (a 47.6% reduction).

Some results of implementing energy and hydraulic efficiency measures are reported here from the literature. Some generic values of energy savings associated with water supply systems were presented at the Brazilian National Energy Plan 2030 [117], originally published by Xenergy [118], and are summarized in Table 3.

Similar to the Brazilian publication, the New York State Energy Research & Development Authority [93] presented a set of measures of energy management for water supply and wastewater treatment systems; these measures and the associated potential estimated savings are presented in Table 4.

The non-profit organization Alliance to Save Energy [119] presented some case results from the Watergy Program, whose purpose is to promote water and energy efficiency in water supply systems through technical and managerial changes. The results are summarized in Table 5.

The results of energy efficiency and conservation actions are variable, depending on the context of each case considered (in this study, we considered the conventional water supply systems context, which differs, for example, from industrial and residential systems). This context (and its influence on the results and potential of energy efficiency actions) depends on the geopolitical location of the case and on the economic environment as well as the nature of the actions themselves.

Tonn and Peretz [120] evaluated the energy conservation potential for the United States, concluding that the potential savings due to energy efficiency standard programs can vary from 20% to 30% in residential and industrial contexts. The authors also concluded that 20% savings and cost ratios of 1:3 are expected in energy efficiency programs and that this potential might be underestimated.

Weber [121] proposed that the overall economic potential of energy conservation within the member countries of the Organization for Economic Co-operation and Development (OECD) is approximately 30%. To evaluate the 30% reference proposed by Weber [121], Dias et al. [122] performed the mathematical modeling of empirical data according to the human development index (HDI), the gross domestic product (GDP) and the energy consumption, which were obtained from the United Nations database. For the potential energy conservation index calculation, they obtained a value of 29.3%, which is very close to the value proposed by Weber [121].

Frijns et al. [29] presented a series of cases of energy efficiency and energy conservation actions developed in Europe, considering the potential for realistic gains between 5% and 25% in the water industry. Generally, similar values in the energy saving potential can be observed among the cited papers, with typical values between 20% and 30%. To interpret some of the empirical results of energy efficiency conservation actions as applicable to CWSSs as well as the impacts on these systems, we assume three classes of energy savings, based on the works previously cited:

- Low impact: estimated energy savings $< 20\%$;
- Medium impact: $20\% \leq$ estimated energy savings $\leq 30\%$;
- High impact: estimated energy savings $> 30\%$.

Table 6 associates the energy efficiency and conservation technological alternatives (EECTA) applicable to CWSSs and analyzed in Section 3, with each energy efficiency and conservation action (EECA) presented in Tables 3 and 4. This table also associates the estimated energy conservation potential with the

Table 4
Generic potential energy savings in water supply systems (adapted from [93]).

Water and energy efficiency actions	Results
Real-time energy monitoring	Energy savings from 5% to 20%
The use of high efficiency motors	Energy savings must be, at least, from 5% to 10%
The use of variable speed motor-pump sets	Energy savings from 10% to 50%
The operational optimization of pumping systems	Energy savings typically from 15% to 30%, possibly up to 70%
Pumps flow variation through VSDs instead of valve throttling	Energy savings vary, possibly more than 50%

Table 5
The empirical results of some energy efficiency projects in WSSs (adapted from [119]).

Region	Water and energy efficiency actions	Results
South Africa, Emfuleni	Pressure management	Energy savings: 14,000 MWh $year^{-1}$ Water savings: 8×10^6 m^3 $year^{-1}$ Avoided GHG emissions: 12,000 t Investment payback time: < 3 months
Brazil, Fortaleza	Operational optimization through automation and control systems	Energy savings: 22,000 MWh $year^{-1}$
Mexico, Veracruz	The use of efficient equipment, variable speed motor-pump sets, operation automation, leakage detection and repair, network modularization in sectors and pressure management.	Energy savings: 24,000 MWh $year^{-1}$ (24% reduction) Energy intensity reduction: from 0.48 kWh m^{-3} to 0.39 kWh m^{-3} Motor-pumps efficiency increase due to variable speed operation: from 45% to 72%

Table 6
Energy efficiency and conservation, technological alternatives and actions applicable to CWSSs according to intervention levels.

EECTA	EECA	Estimated energy savings	Impact	Intervention level (according to Dias [15])
The use of renewable energy sources for pumping	The use of wind or solar pumping	Highly variable, according to the local potential	Low to high	3
Hydropower recovery	The installation of hydraulic turbines and generators in existing water supply adduction systems	Highly variable, according to the system layout and local potential	Low to high	3
Pressure and water losses management	Pressure reduction (by the use of PRVs, water tank level or pumping adjustments), pipe repair or substitution, active leakage control	Assuming that the energy savings are proportional to the water savings, we assume a 25% to approximately 50% saving potential, as presented by Marunga et al. [115] and Girard and Stewart [116]	Medium to high	1 and 2
Operational optimization	Real-time energy monitoring	5–20%	Low to medium	2
	The operational optimization of pumping systems	15–30%	Low to medium	2
The use of efficient motor-pump sets	Correct pump sizing	15–25%	Low to medium	2
	The substitution of actual pumps for a most efficient pump or with the best efficiency operation point, compatible with the systems operation point	2–10%	Low	2
	Replacing the belts by direct coupling	1%	Low	2
	Replacing the worn impellers. Checking the bearings, mechanical seals and other seals.	1–6%	Low	2
	The use of high efficiency motors	5–10%	Low	2
The use of variable speed motor-pump sets	The use of variable speed drives instead of valves	30–80%	Medium to high	2
The optimization of storage capacity and reservoir operation	The use of tanks for flow control and storage,	10–20%	Low to medium	2
Optimized pipe and network designs	The elimination of bypass loops and other unnecessary flows.	10–20%	Low to medium	2
	Increasing the pipe diameters	5–20%	Low to medium	2
	Reductions in the oversizing design parameter limits for defining the system capacity	5–10%	Low	2

impact classes proposed and classifies each EECA according to the intervention levels proposed by Dias [15].

By inspecting Table 6, it can be determined that several of the analyzed EECAs were classified in intervention level 2 (increasing the efficiency of power-consuming units), which, according to Dias [15], reveals that such EECAs are relatively inexpensive, simple for deployment and result in proportionally large energy savings. However, it appears that the expected impacts of these EECAs are generally low or medium, which does not confirm this assumption.

Pressure and water loss management were alternatives, classified in intervention levels 1 and 2 of Dias [15], and their implementation imposes large impacts on the energy efficiency of the system. This finding indicates that the pressure and water loss management should be considered a priority EE and EC alternative for CWSSs managers.

The use of renewable sources for pumping and hydraulic energy recovery, which are representative of intervention level 3 (increasing the efficiency of power generation units), can provide energy impacts with high variability, according to the local potential. In this sense, the energy impacts of the EECTAs can be generalized as medium, which is consistent with level 3 interventions.

5. Conclusions

This paper presented the state-of-the-art approaches to energy efficiency and conservation in conventional water supply systems, providing an overview of EECTAs from the analysis of selected research results, which approach these alternatives individually.

The various energy efficiency and conservation alternatives applicable to conventional water supply systems are technologically dominated and widely reported in the literature. Such alternatives range from simple (but effective) repairs in pipes for the elimination of leaks to modern real-time operational optimization techniques. Water losses are the most emblematic source of water and energy waste in CWSSs, and reductions in water losses must be a priority efficiency action. Nevertheless, large volumes of water and electricity are lost in CWSSs throughout the world.

Two main reasons are suggested to explain the energetic and hydraulic inefficiency scenario:

- The deployment costs of EECAs are not attractive from the perspective of system managers and decision makers, and the costs related to water and energy losses are passed on to consumers through water bills. Additionally, from a financial standpoint, the main input of CWSSs (raw water) is, in many cases, obtained for free, which makes investments in its conservation unjustifiable.
- The watersheds in which CWSSs are located generally still have satisfactory water availability. The environmental and social importance of water and electricity are only considered in addition to the economic factor during scarcity scenarios.

Some evidence presented throughout this paper strengthens these two hypotheses, such as the concept of economic leakage levels and the fact that most optimization models presented in the literature aim to minimize the costs associated with electricity, instead of minimizing the electricity consumption itself.

This hypothesis and the supporting evidence suggests that sustainability, i.e., the management of CWSSs by balancing the economic, environmental and social issues, is not yet fully considered in the management of water supply systems, which is unlike economic and financial issues.

Acknowledgments

The authors are grateful to São Paulo Research Foundation (FAPESP) for the Regular Research Award (Process 2013/07287-3). The second author is also indebted to National Council for Scientific and Technological Development (CNPq) for his research grant (Process 302939/2011-3.

References

[1] Alliance to Save Energy. 2002. Water and energy: harnessing the opportunities for unexplored water and energy efficiency in municipal water systems. Washington: Alliance; 2002 [in Portugese].
[2] Brandt M, Middleton R, Wheale G, Schulting F. Energy efficiency in the water industry, a global research project. Water Pract Technol 2011;6(2). http://dx.doi.org/10.2166/wpt.2011.028.
[3] Gomes HP. Pumping systems: energy efficiency. João Pessoa: Editora Universitária UFPB; 2009(in Portuguese).
[4] Shrestha E, Ahmadn S, Johnson W, Batista JR. The carbon footprint of water management policy options. Energy Policy 2012;42:201–12.
[5] Bates BC, Kundzewicz ZW, Wu S, Palutikof JP. Climate change and water: technical paper of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat; 2008.
[6] Kenway SJ, Lant PA, Priestley A, Daniels P. The connection between water and energy in cities: a review. Water Sci Technol 2011;63(9):1983–90.
[7] Gude VG, Nirmalakhandan N, Deng S. Renewable and sustainable approaches for desalination. Renew Sustain Energy Rev 2010;14(9):2641–54.
[8] Plappally AK, Lienhard JH. Energy requirements for water production, treatment, end use, reclamation and disposal. Renew Sustain Energy Rev 2012;16(7):4818–48.
[9] Racoviceanu AI, Karney BW, Kennedy CA, Colombo AF. Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems. J Infrastruct Syst 2007;13(4):261–70.
[10] Mo W, Zhang Q, Mihelcic JR, Hokanson DR. Embodied energy comparison of surface water and groundwater supply options. Water Res 2011;45(17):5577–86.
[11] Scott CA, Pierce SA, Pasqualetti MJ, Jones AL, Montz BE, Hoover JH. Policy and institutional dimensions of the water–energy nexus. Energy Policy 2011;39(10):6622–30.
[12] Venkatesh G, Brattebø H. Energy consumption, costs and environmental impacts for urban water cycle services: case study of Oslo (Norway). Energy 2011;36(2):792–800.
[13] Brasil, Secretaria Nacional de Saneamento Ambiental. National Information System on Sanitation: diagnosis of water services and sewage – 2010. Brasília: MCIDADES, SNSA; 2012 [in Portuguese].
[14] United Nations. The Millennium Development Goals Report 2011. New York: UN; 2011.
[15] Dias RA. Impacts of equipment replacement in the energy conservation process [M.Sc. Dissertation Mechanical Engineering]. Faculdade de Engenharia de Guaratinguetá, Universidade Estadual Paulista, Guaratinguetá; 1999 [in Portuguese].
[16] Brasil, Fundação Nacional de Saúde. Sanitation Handbook. Third edition. Brasília: FUNASA, 2006 [in Portuguese].
[17] Anderson JM. Integrating recycled water into urban water supply solutions. Desalination 2006;187(1-3):1–9.
[18] Hernández-Sancho F, Sala-Garrido R. Technical efficiency and cost analysis in wastewater treatment processes: a DEA approach. Desalination 2009;249(1):230–4.
[19] Hernández-Sancho F, Molinos-Senante M, Sala-Garrido R. Energy efficiency in Spanish wastewater treatment plants: a non-radial DEA approach. Sci Total Environ 2011;409(14):2693–9.
[20] Kajenthira A, Siddiqi A, Anadon LD. A new case for promoting wastewater reuse in Saudi Arabia: bringing energy into the water equation. J. Environ Manag 2012;102(15):184–92.
[21] Lundin M, Morrison GM. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. Urban Water 2002;4(2):145–52.
[22] Filion YR, MacLean HL, Karney BW. Life-cycle energy analysis of a water distribution system. J Infrastruct Syst 2004;10(3):120–30.
[23] Stokes J, Horvath A. Life-cycle assessment of urban water provision: tool and case study in California. J Infrastruct Syst 2011;17(1):15–24.
[24] Makropoulos CK, Butler D. Distributed water infrastructure for sustainable communities. Water Resour Manag 2010;24(11):2795–816.
[25] Retamal M, Turner A. Unpacking the energy implications of distributed water infrastructure: how are rainwater systems performing? Water Sci Technol 2010;10(4):546–53.
[26] Filion YR. Impact of urban form on energy use in water distribution systems. J Infrastruct Syst 2008;14(4):337–46.
[27] Proença LC, Ghisi E, Tavares DF, Coelho GM. Potential for electricity savings by reducing potable water consumption in a city scale. Resour Conserv Recycl 2011;55(11):960–5.
[28] Cabrera E, Pardo MA, Cobacho R, Cabrera Jr E. Energy audit of water networks. J Water Resour Plan Manag 2010;136(6):669–77.
[29] Frijns J, Middleton R, Uijterlinde C, Wheale G. Energy efficiency in the European water industry: learning from best practices. J Water and Clim Chang 2012;3(1):11–7.
[30] Montalvo I, Izquierdo J, Schwarze S, Pérez-García R. Multi-objective particle swarm optimization applied to water distribution systems design: an approach with human interaction. Math Comput Model 2010;52(7-8):1219–27.
[31] Gomes HP, Silva JG. Economic design of water distribution systems considering variable boundary conditions in the project. Rev Bras Recur Hidr 2006;11(2):99–110(in Portuguese).
[32] Mohan S, Babu KSJ. Optimal water distribution network design with honey-bee mating optimization. J Comput Civ Eng 2010;24(1):117–26.
[33] Burgschweiger J, Gnädig B, Steinbach MC. Optimization models for operative planning in drinking water networks. Optim Eng 2009;10(1):43–73.
[34] Carrijo IB, Reis LFR. Optimal operational strategies of water distribution systems using multi-objective genetic algorithms and machine learning – implementing the system of macro-water distribution of Goiânia. Rev Bras Recur Hidr 2006;11(2):161–72(in Portuguese).
[35] Costa LHM, Castro MAH, Ramos H. Using a hybrid genetic algorithm for optimal operation of water supply systems. Eng Sanitária Ambiental 2010;15(2):187–96(in Portuguese).
[36] Costa LHM, Ramos HM, Castro MAH. Hybrid genetic algorithm in the optimization of energy costs in water supply networks. Water Sci Technol 2010;10(3):315–26.
[37] Moreno MA, Planells P, Córcoles JI, Tarjuelo JM, Carrión PA. Development of a new methodology to obtain the characteristic pump curves that minimize the total cost at pumping stations. Biosyst Eng 2009;102(1):95–105.
[38] Savar M, Kozmar H, Sutlovic I. Improving centrifugal pump efficiency by impeller trimming. Desalination 2009;249(2):654–9.
[39] Kaya D, Yagmur EA, Yigit KS, Kilic FC, Eren AS, Celik C. Energy efficiency in pumps. Energy Convers Manag 2008;49(6):1662–73.
[40] Colombo AF, Karney BW. Impacts of leaks on energy consumption in pumped systems with storage. J Water Resour Plan Manag 2005;131(2):146–55.
[41] Araujo LS, Ramos H, Coelho ST. Pressure control for leakage minimisation in water distribution systems management. Water Resour Manag 2006;20(1):133–49.
[42] Fontana N, Giugni M, Portolano D. Losses reduction and energy production in water-distribution networks. J Water Resour Plan Manag 2012;138(3):237–44.
[43] Hammad M. Photovoltaic, wind and diesel: a cost comparative study of water pumping options in Jordan. Energy Policy 1995;23(8):723–6.
[44] Velasco M, Probst O, Acevedo S. Theory of wind-electric water pumping. Renew Energy 2004;29(6):873–93.
[45] Purohit P, Kandpal C. Renewable energy technologies for irrigation water pumping in India: projected levels of dissemination, energy delivery and investment requirements using available diffusion models. Renew Sustain Energy Rev 2005;9(6):592–607.
[46] Kumar A, Kandpal TC. Renewable energy technologies for irrigation water pumping in India: a preliminary attempt towards potential estimation. Energy 2007;32(5):861–70.
[47] Purohit P. Financial evaluation of renewable energy technologies for irrigation water pumping in India. Energy Policy 2007;35(6):3134–44.
[48] Ramos JS, Ramos HM. Sustainable application of renewable sources in water pumping systems: optimized energy system configuration. Energy Policy 2009;37(2):633–43.
[49] Granich W, Elmore AC. An evaluation of the use of renewable energy to pump water in Sacala las Lomas, Guatemala. Environ Earth Sci 2010;61(4):837–46.
[50] Lara DD, Merino GG, Pavez BJ, Tapia JA. Efficiency assessment of a wind pumping system. Energy Convers Manag 2011;52(2):795–803.
[51] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. Renew Sustain Energy Rev 2006;10(4):312–40.
[52] Vilela OC, Fraidenraich N. A methodology for the design of photovoltaic water supply systems. Prog Photovolt Res Appl 2001;9(5):349–61.
[53] Mahmoud E, el Nather H. Renewable energy and sustainable developments in Egypt: photovoltaic water pumping in remote areas. Appl Energy 2003;74(1-2):141–7.
[54] Odeh I, Yohanis YG, Norton B. Economic viability of photovoltaic water pumping systems. Sol Energy 2006;80(7):850–60.
[55] Ghoneim AA. Design optimization of photovoltaic powered water pumping systems. Energy Convers Manag 2006;47(11-12):1449–63.
[56] Glasnovic Z, Margeta J. Optimization of irrigation with photovoltaic pumping system. Water Resour Manag 2007;21(8):1277–9.
[57] Ould-Amrouche S, Rekioua D, Hamidat A. Modelling photovoltaic water pumping systems and evaluation of their CO_2 emissions mitigation potential. Appl Energy 2010;87(11):3451–9.

[58] Vieira F, Ramos HM. Hybrid solution and pump-storage optimization in water supply system efficiency: a case study. Energy Policy 2008;36(11):4141–8.
[59] Ramos HM, Kenov KN, Vieira F. Environmentally friendly hybrid solutions to improve the energy and hydraulic efficiency in water supply systems. Energy Sustain Dev 2011;15(4):436–42.
[60] Ulanicki B, Bounds PLM, Rance JP, Reynolds L. Open and closed loop pressure control for leakage reduction. Urban Water 2000;2(2):105–14.
[61] Giustolisi O, Savic D, Kapelan Z. Pressure-driven demand and leakage simulation for water distribution networks. J Hydraul Eng 2008;134(5):626–35.
[62] Obradovic D. Modelling of demand and losses in real-life water distribution systems. Urban Water 2000;2(2):131–9.
[63] Nazif S, Karamouz M, Tabesh M, Moridi A. Pressure management model for urban water distribution networks. Water Resour Manag 2010;24(3):437–58.
[64] Nicolini M, Giacomello C, Deb K. Calibration and optimal leakage management for a real water distribution network. J Water Resour Plan Manag 2011;137(1):134–42.
[65] Nicolini M, Zovatto L. Optimal location and control of pressure reducing valves in water networks. J Water Resour Plan Manag 2009;135(3):178–87.
[66] Lambert AO, Brown TG, Takizawa M, Weimer D. A review of performance indicators for real losses from water supply systems. Aqua 1999;48(6):227–37.
[67] Venkatesh G. Cost-benefit analysis – leakage reduction by rehabilitating old water pipelines: case study of Oslo (Norway). Urban Water J 2012;9(4):277–86.
[68] Li W, Ling W, Liu S, Zhao J, Liu R, Chen Q, et al. Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: a case study. J Environ Sci 2011;23(11):1816–22.
[69] Gao Y, Brennan MJ, Joseph PF, Muggleton JM, Hunaidi O. On the selection of acoustic/vibration sensors for leak detection in plastic water pipes. J Sound Vib 2005;283(3-5):927–41.
[70] Gao Y, Brennan MJ, Joseph PF. A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes. J Sound Vib 2006;292(3-5):552–70.
[71] Hunaidi O, Chu WT. Acoustical characteristics of leak signals in plastic water distribution pipes. Appl Acoust 1999;58(3):235–54.
[72] Ashton CH, Hope VS. Environmental valuation and the economic level of leakage. Urban Water 2001;3(4):261–70.
[73] Lingireddy S, Wood DJ. Improved operation of water distribution systems using variable-speed pumps. J Energy Eng 1998;124(3):90–103.
[74] Jowitt PW, Xu C. Optimal valve control in water distribution networks. J Water Resour Plan Manag 1990;116(4):455–72.
[75] Vairavamoorthy K, Lumbers J. Leakage reduction in water distribution systems: optimal valve control. J Hydraul Eng 1998;124(11):1146–54.
[76] Eker I, Kara T. Operation and control of a water supply system. ISA Trans 2003;42(3):461–73.
[77] Vieira F, Ramos HM. Optimization of the energy management in water supply systems. Water Sci Technol 2009;9(1):59–65.
[78] Vieira F, Ramos HM. Optimization of operational planning for wind/hydro hybrid water supply systems. Renew Energy 2009;34(3):928–36.
[79] Haestad methods. Advanced water distribution modeling and management. Waterbury: Haestad Methods; 2003.
[80] Herrera M, Torgo L, Izquierdo J, Pérez-Garcıa R. Predictive models for forecasting hourly urban water demand. J Hydrol 2010;387(1-2):141–50.
[81] Campisano A, Creaco E, Modica C. RTC of valves for leakage reduction in water supply networks. J Water Resour Plan Manag 2010;136(1):138–41.
[82] Giacomello C, Kapelan Z, Nicolini M. Fast hybrid optimisation method for effective pump scheduling. J Water Resour Plan Manag 2013;139(2):175–83.
[83] Tabesh M, Yekta AHA, Burrows R. An integrated model to evaluate losses in water distribution systems. Water Resour Manag 2009;23(3):477–92.
[84] de la Torre A. Efficiency optimization in SWRO plant: high efficiency & low maintenance pumps. Desalination 2008;221(1-3):151–7.
[85] Associação Brasileira de Normas Técnicas. NBR 12214: system design pumping water for public supply. Rio de Janeiro: ABNT; 1992 [in Portuguese].
[86] Saidur R. A review on electrical motors energy use and energy savings. Renew Sustain Energy Rev 2010;14(3):877–98.
[87] Garcia AGP, Szklo AS, Schaeffer R, McNeil MA. Energy-efficiency standards for electric motors in Brazilian industry. Energy Policy 2007;35(6):3424–39.
[88] European Committee of Manufacturers of Electrical Machines and Power Electronics. Electric motors and variable speed drives: standards and legal requirements for the energy efficiency of low-voltage three-phase motors. Frankfurt: CEMEP; 2011.
[89] European Association of Pump Manufacturers (EUROPUMP). Ecodesign; 2012. Available from: 〈http://europump.net/energy-policy/ecodesign〉.
[90] European Comission. Ecodesign Directive; 2012. Available from: 〈http://lot29.ecopumps.eu/〉.
[91] Gibson IH. Variable-speed drives as flow control elements. ISA Trans 1994;33(2):165–9.
[92] Fang H, Zhang J, Gao J. Optimal operation of multi-storage tank multi-source system based on storage policy. J Zhejiang Univ Sci A (Appl Phys Eng) 2010;11(8):571–9.
[93] New York State Energy Research & Development Authority. Water & Wastewater Energy Management: Best Practices Handbook. New York: NYSERDA; 2010.
[94] Batchabani E, Fuamba M. Optimal tank design in water distribution networks: review of literature and perspectives. J Water Resour Plan Manag 2012. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000256.
[95] Vamvakeridou-Lyroudia LS, Savic DA, Walters GA. Tank simulation for the optimization of water distribution networks. J Hydraul Eng 2007;133(6):625–36.
[96] di Pierro F, Khu S, Savic D, Berardi L. Efficient multi-objective optimal design of water distribution networks on a budget of simulations using hybrid algorithms. Environ Model Softw 2009;24(2):202–13.
[97] Keedwell E, Khu S. A hybrid genetic algorithm for the design of water distribution networks. Eng Appl Artif Intell 2005;18(4):461–72.
[98] Gupta I, Gupta A, Khanna P. Genetic algorithm for optimization of water distribution systems. Environ Model Softw 1999;14(5):437–46.
[99] Samani HMV, Mottaghi A. Optimization of water distribution networks using integer linear programming. J Hydraul Eng 2006;132(5):501–9.
[100] Zecchin AC, Simpson AR, Maier HR, Leonard M, Roberts AJ, Berrisford MJ. Application of two ant colony optimization algorithms to water distribution system optimization. Math Comput Model 2006;44(5-6):451–68.
[101] Chu C, Lin M, Liu G, Sung Y. Application of immune algorithms on solving minimum-cost problem of water distribution network. Math Comput Model 2008;48(11-12):1888–900.
[102] Baños R, Gil C, Reca J, Montoya FG. A memetic algorithm applied to the design of water distribution networks. Appl Soft Comput 2010;10(1):261–6.
[103] Bolognesi A, Bragalli C, Marchi A, Artina S. Genetic heritage evolution by stochastic transmission in the optimal design of water distribution networks. Adv Eng Softw 2010;41(5):792–801.
[104] Cisty M. Hybrid genetic algorithm and linear programming method for least-cost design of water distribution systems. Water Resour Manag 2010;24(1):1–24.
[105] Prasad TD. Design of pumped water distribution networks with storage. J Water Resour Plan Manag 2010;136(1):129–32.
[106] Walski TM. The wrong paradigm – why water distribution optimization doesn't work. J Water Resour Plan Manag 2001;127(4):203–5.
[107] Rossman LA. Epanet 2 users manual. Cincinnati: United States Environmental Protection Agency; 2000.
[108] Afshar MH, Akbari M, Mariño MA. Simultaneous layout and size optimization of water distribution networks: engineering approach. J Infrastruct Syst 2005;11(4):221–30.
[109] Bai D, Yang P, Song L. Optimal design method of looped water distribution network. Syst Eng Theory Pract 2007;27(7):137–43.
[110] Wu W, Simpson A, Maier H, Marchi A. Incorporation of variable-speed pumping in multiobjective genetic algorithm optimization of the design of water transmission systems. J Water Resour Plan Manag 2012;138(5):543–52.
[111] Saidur R, Mahlia TMI. Energy, economic and environmental benefits of using high-efficiency motors to replace standard motors for the Malaysian industries. Energy Policy 2010;38(8):4617–25.
[112] Hasanuzzaman M, Rahim NA, Saidur R, Kazi SN. Energy savings and emissions reductions for rewinding and replacement of industrial motor. Energy 2011;36(1):233–40.
[113] Kucukali S. Hydropower potential of municipal water supply dams in Turkey: a case study in Ulutan Dam. Energy Policy 2010;38(11):6534–9.
[114] Kucukali S. Municipal water supply dams as a source of small hydropower in Turkey. Renew Energy 2010;35(9):2001–7.
[115] Marunga A, Hoko Z, Kaseke E. Pressure management as a leakage reduction and water demand management tool: the case of the City of Mutare, Zimbabwe. Phys Chem Earth 2006;31(15-16):763–70.
[116] Girard M, Stewart RA. Implementation of pressure and leakage management strategies on the Gold Coast, Australia: case study. J Water Resour Plan Manag 2007;133(3):210–7.
[117] Brasil, Ministério de Minas e Energia, Empresa de Pesquisa Energética. National Energy Plan 2030. Brasília: MME, EPE; 2007 [in Portuguese].
[118] XENERGY. United States Industrial Motor Systems Market Opportunities Assessment. Burlington: US-DOE; 1998.
[119] Alliance do Save Energy. WATERGY: Energy and water efficiency in municipal water supply and wastewater treatment: Cost-effective savings of water and energy. Washington: Alliance; 2007.
[120] Tonn B, Peretz JH. State-level benefits of energy efficiency. Energy Policy 2007;35(7):3665–74.
[121] Weber L. Some reflections on barriers to the efficient use of energy. Energy Policy 1997;25(10):833–5.
[122] Dias RA, Mattos CR, Balestieri JAP. The limits of human development and the use of energy and natural resources. Energy Policy 2006;34(9):1026–31.